Technology Needs of Planetary Missions of the 21st Century[1]

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Abstract—This paper presents the findings of a series of planetary mission studies supporting development and update of NASA's Space Science Enterprise Strategic Plan. The studies evaluate feasibility, science return, cost, and benefits of advanced technology for missions that are candidates for inclusion in the strategic plan. Emphasis (to date) has been on nine target missions identified in the plan for launch after 2004. Mission concepts have been defined for each target, and the enabling and enhancing technologies developments have been identified. It was found that the current trend toward miniaturization of avionics will benefit all missions. Several missions were found to be enabled or strongly enhanced by advances in low thrust propulsion, either solar electric or solar sail. Another critical area is in-situ technologies, including precision approach; landing; surface mobility; sample collection, analyses and packaging; and sample return to Earth.

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1. INTRODUCTION

NASA recently published a strategic plan for space science that calls for an integrated effort by mission designers and technology developers to carry out a set of high priority science missions, many of which are not feasible with current technology. Part of the analytical basis for the strategic plan was a series of studies of planetary missions aimed at confirming the feasibility of candidate missions and at identifying technology advances needed to make each mission concept into a serious candidate for implementation. The studies are continuing to improve understanding of technology benefits and to prepare for an update of the strategic plan to be completed by mid-2000. This paper reports on the results to date of the studies, which have included missions to all the planets except Mars (covered by a different office at JPL) and Pluto (technology needs for the planned 2004 launch to Pluto are well understood), as well as to comets and asteroids. A brief description of each mission concept is provided, followed by a discussion of its technology elements. A wrap-up is included showing where particular technology advances can support more than one mission.

The science objectives and requirements for each mission concept were established via consultation with NASA's Solar System Exploration Subcommittee and its working groups. NASA gives highest priority to "enabling" technologies, but this term requires some definition. In order to implement the strategic plan with projected budgets, it has been guidelined that no launch vehicle larger than a Delta 3 should be used. For the purpose of these studies a technology element was considered enabling for a particular mission if it facilitates achievement of the principal science objectives using a Delta 3 or smaller launch vehicle.

2. MISSION CONCEPTS AND TECHNOLOGY NEEDS

A brief description of each mission concept and a summary of the corresponding technology needs is provided here. Detailed quantitative requirements or goals for technology development are provided in tabular form in the appendix.

Comet Nucleus Sample Return (CNSR)

A Comet Nucleus Sample Return mission would obtain kilogram scale samples - taken from one or more sampling sites - using a subsurface sampling apparatus such as a drill or a tethered penetrator. Challenging science goals for the mission include deep drilling (to 10 m) and obtaining samples from multiple sites. A mother ship would return the samples to Earth. A wide range of mission profiles including variations of the relative intelligence of the mother ship and the surface elements have been suggested.

Because of the large propulsive energy (Delta V) requirements associated with first rendezvousing with a comet and then returning to Earth, advanced solar-powered propulsion technology is enabling for all comets of interest to the science community. (Nuclear reactor powered propulsion could also be applicable but is not currently being considered for NASA science missions.) The most likely form of this would involve advances relative to the current state-of-the-art of solar electric propulsion (SEP) with a specific weight goal of 30 kg/KW (including the power system). Improvements on solar array performance can contribute to this goal. Techniques for approach, landing, anchoring, sample collection, and sample preservation were also identified as enabling for this mission. Many of these are well along the development path and will be demonstrated in the DS-4 mission, launching in 2003. In the far term, a solar sail would offer the capability of accomplishing the mission with a smaller launch vehicle and potentially a shorter flight time but with the penalty that the mother ship could not be active during the rendezvous, eliminating some sampling schemes.

Small Body Coring and Advanced Sampling

The strategic plan envisions a continuing series of sampling missions to comets and asteroids. These are clear examples of missions that will not go until the technology is ready, and the critical developments are in the area of in situ chemical analyzers (for sample context and comparison with returned material), deep drilling (to 10-100m or more to assure acquisition of pristine material), and sample core acquisition and preservation for sample elements ranging from soft ice to metallic.

Jupiter Deep Multi-probes

The Jupiter Deep Multi-Probes mission would send two or three probes to 50-100 bar depths at different latitudes, expanding upon the Galileo probe science (20 bar).

Technology for planetary entry probes has not advanced much beyond the Galileo and Cassini level, but fundamentals are available to create a new generation of probes that would enable the kind of multiprobe mission envisioned here with an affordable launch vehicle. Two major areas need work: the thermal protection system, with a goal of heat shield mass less than 35% of the total probe mass, and avionics/instruments, particularly the mass spectrometer with a goal of 5 kg, including all related plumbing, pumps, etc. Also, telemetry from 100 bar may require improvements in current L-band or UHF technology.

Solar-Mercury Mission

This would be a Mercury polar-orbiting spacecraft with a full suite of remote sensing and fields and particles instruments to generate a detailed global characterization of the planet as well as study solar phenomena. This mission occupies an important niche in the roadmaps of both the Solar System Exploration and Sun-Earth Connection communities. The baseline concept places the spacecraft in a 200 x 10,000 km orbit with periapsis near the equator. The high apoapsis provides for rejection of heat absorbed near the surface of the planet. The spacecraft is 3-axis stabilized with a rotating platform for some of the fields and particles instruments.

This is another case where advances in solar powered propulsion can enable the ambitious mission laid out by the science committees; and, while advances in SEP will probably be adequate, development of an interplanetary solar sail capability would add significantly to our ability to return science information from Mercury. Also, in order to reduce the launch mass to acceptable levels, the thermal issues must be dealt with more efficiently than current technology allows. This could include advances in high temperature solar arrays (which could be pointed more closely to the sun with a corresponding size reduction), thermal control techniques and materials, and high temperature avionics.

Europa Lander

A Europa Lander would conduct chemical analyses of near-surface ice and organics and would study the interior structure of the moon. In the most ambitious concepts, a "cryobot" would melt or burrow through the ice to explore the (hypothetical) underlying ocean. The trajectory being considered would insert into Jupiter orbit and use a series of satellite flybys lasting approximately 1 year to remove energy from the orbit prior to a descent to the surface. Regardless of the main propulsion system used to reach Jupiter, a significant portion of the launch mass would be allocated to transporting a chemical propulsion system to Jupiter for these operations.

Technology advances are needed on a broad front to enable a landed mission on Europa. The mission is very demanding energetically, calling for a combination of lightweight, radiation-tolerant systems and improvements in the performance and hardware mass of chemical propulsion. Many of the concepts examined would benefit from availability of small radioisotope based power systems (<10 watts). Navigation to the landing site is also a significant challenge, but perhaps the most critical area is for development of systems to perform the desired science. This includes, in most concepts, systems to acquire samples of ice from a meter or so below the surface, to concentrate the samples, and to perform a broad range of organic chemical analyses. In the long term, it also can include "cryobot" systems for getting through the ice and "hydrobot" systems for ocean exploration.

Io Volcanic Observer

The Io Volcanic Observer would use visible and thermal imaging, high resolution ultraviolet spectroscopy, and radio tracking to study Io's volcanoes, atmosphere, and gravity fields and their interactions. Substantial improvements are needed in lightweight, radiation-tolerant spacecraft systems before this mission can be contemplated. The stronger radiation at Io makes this even more demanding than the Europa mission.

Neptune Orbiter/Triton Exploration

This mission would use a full complement of remote sensing instruments to characterize both the planet and its largest moon. To accomplish this with affordable launch vehicles and acceptable mission duration we need a very low mass spacecraft (as envisioned in the current work on "system-on-a-chip" technology), advanced solar powered propulsion systems (using SEP or solar sail in one or more close in orbits of the sun to accelerate the spacecraft for a quick trip to Neptune), and aerocapture into Neptune orbit. Return of a high volume of science information from the distance of Neptune represents a major challenge especially when coupled with the necessary mass reduction. The study emphasized use of optical communication along with advanced techniques for selection, editing, and compression of the data.

Titan Organic Explorer

A Titan Explorer would primarily study the distribution and composition of organics on the Saturnian moon, as well as look at the dynamics of the global winds. Aerocapture at Titan, avoiding a Saturn orbit insertion, is currently the most attractive trajectory option.

A variety of mission profiles have been proposed for Titan based on a variety of models of surface and atmospheric states. Cassini data will shed light on the validity of these models, but in the mean time, because of the importance of Titan as a potential host for prebiotic chemistry, it makes sense to take the early steps toward a quick follow-on to Cassini. This includes work on organic chemistry analysis systems (some overlap with work needed for Europa) and on delivery systems including aerocapture, balloon systems, and landers. For some concepts small radioisotope power sources will also be enabling.

Venus Laboratories

While Venus has already been the target of several exploration missions, the operational difficulties associated with its high temperatures and opaque, corrosive cloud layers have left many important scientific questions regarding its geology and climate unanswered.

One mission concept proposes an aerobot system (a balloon filled with a reversible phase fluid) to provide an imaging platform below the clouds as well as operations at or near the surface as part of a long term mission with excursions above the clouds for thermal recycling. This concept needs technology work in several areas including reversible fluid thermodynamics, acid-resistant balloon materials, gondola thermal control, miniaturized high temperature avionics, balloon communications and navigation, and balloon snake systems. (A balloon snake drags on the ground to maintain neutral buoyancy. Advanced concepts would include soil sampling and analysis devices in the snake.)

3. Conclusions

Table 1 summarizes the enabling technologies identified in the mission studies. Development of the set of "enabling" technologies for a particular mission would make available key science capabilities that do not currently exist and/or provide for fitting the mission on an affordable launch vehicle. Some generalizations on the entries in the chart are in order:

(1) Advances in microavionics are beneficial to all missions but are particularly important for targets far from the sun, especially where large Delta Vs are needed at the target, e.g., Europa Lander. (Every kg of mass subtracted from the Europa Lander avionics reduces the launch mass by 15 kg.) Reduced hardware mass and increased specific impulse for the chemical propulsion systems used for orbit insertion and/or descent are also very important for these cases.

(2) Either advanced SEP or solar sailing could satisfy the needs of several missions. This is particularly important for the Mercury Orbiter where solar powered propulsion can be used for approaching the planet at a low relative velocity and also for orbit insertion (thus eliminating the need for a prohibitively heavy chemical propulsion system). Advanced solar powered propulsion is also enabling to return to Earth after rendezvousing with a comet for sample collection and also for fast trips to the outer planets with affordable launch vehicles.

(3) Improved solar array performance is an important element of all the SEP cases and high temperature solar array capability is critical for Mercury and Venus.

(4) Missions to the outer planets (Jupiter and beyond) require completion of the work on advanced radioisotope power systems (ARPS) now underway in NASA's Deep Space Systems Technology (X2000) Program. Substitution of even the most optimistic solar-based power system would push the launch masses of these

missions beyond the capability of affordable launch vehicles. ARPS also trades favorably against solar power for extended-duration comet sample acquisition activities.

(5) Missions involving balloons, landers, and sample returns call for broad advances in on-board autonomy. Because of two-way light time considerations, sophisticated autonomous control is required for balloon descent and sample acquisition operations envisioned for Venus and Titan and for all spacecraft descent, ascent, and rendezvous operations.

(6) Several missions cannot be accomplished until we can package more capable instruments for space flight. In particular, we need to shrink a laboratory full of organic chemistry instruments into a 10-20 kg package to be sent to Europa and Titan.

The breadth of the set of enabling technologies shown in Table 1 makes it unlikely that sufficient resources will be available to fully develop all of them simultaneously. This suggests that technology investment planning should be carefully synchronized with prioritization of mission concepts.

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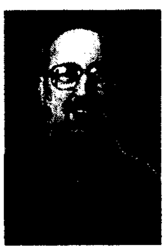

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5. APPENDIX - TECHNOLOGY REQUIREMENTS

Tables A1—A9 present detailed technology requirements and goals based on the mission studies outlined above. The entries are quantitative whenever possible, giving a value or range of values derived from a particular mission concept. The entries are sorted according to the standard NASA database structure (1.1 Power, 1.2 Propulsion, etc).

The criticality levels are defined as follows:

(1) Enabling - provides for achieving the science objectives of the mission with an affordable launch vehicle (Delta 3 or smaller).
(2) Strongly enhancing - provides substantial increase in payload or reduction in cost or risk.
(3) Enhancing.

The technology readiness level (TRL) estimates in the tables conform to the standard NASA definitions:

(1) Basic principles observed and reported.
(2) Technology concept and/or application formulated.
(3) Analytical and experimental critical function and/or characteristic proof-or-concept.
(4) Component and/or breadboard validation in laboratory environment.
(5) Component and/or breadboard validation in relevant environment.
(6) System/subsystem model or prototype demonstration in a relevant environment (ground or space).
(8) Actual system completed and "flight qualified" through test and demonstration (ground or space).
(9) Actual system "flight proven" through successful mission operations.

Table 1. Summary of Enabling Technologies

Mission	Micro Spacecraft Systems	Advanced SEP	Solar Sail	Chemical Propulsion	Sample Acquisition and Handling	Advanced Solar Arrays	Small Lander Power	Advanced Radio-isotope Power	Advanced Heat Shield	Advanced Thermal Control	Aero-capture	On-Board Autonomy *	Advanced Communica-tion	Aerobot System	Micro Chemistry Lab	µMass Spec, Integrat Remote Imaging, or µGeo Lab	Radiation Tolerant Systems
CNSR		(X)	(X)		X	(X)		X				X					
Coring & Advanced Sampling	X	(X)	(X)		X	(X)		X				X			X		
Jupiter Probes	X								X	X						µMS	
Solar Mercury		(X)	(X)			X				X							
Europa Lander	X	(X)	(X)	X	X		X	X				X			X		X
Io Volcano	X			X				X								R	X
Neptune Triton	X	(X)	(X)			(X)		X			X	X	X			R	
Titan Organics	X				X		X	X			X	X		X	X		
Venus Labs	X					X				X		X	X	X		µGL	

* Including categories of autonomous descent/landing and mobility on and within target body

X: Key Technology need

(X): Key Technology need option

Table A1. Comet Nucleus Sample Return Technology Requirements

Technology Element	Technology Area/Item	Performance Metric (Criticality) {Current TRL}
1.1 Power	• Advanced solar arrays • Advanced secondary battery or • Advanced radioisotope power (ARPS)	• 5—10 kg/kW (SEP support) **(1){4}** • Li-ion/80 Whr/kg, 140 Whr/L; 25—30 Ahr **(2){4}** • Efficiency 3X RTG **(1){4}**
1.2 Propulsion	• Advanced SEP and thrusters or • Solar sail	• Midterm: 5 kW, < 30 kg/kW (including power system); long term: 10 kW, < 30 kg/kW (including power system) **(1){4}** • Areal density: < ~ 6g/m^2 **(1){2}**
1.3 Spacecraft avionics	• Data handling/advanced CDS • Miniature propulsion drive electronics	• DRAM cubes (SEU immune); μ-packaging (MCM interconnects); SCSI interface **(2){3}** • < 1 kg and < 2 W **(2){4}**
1.6 Robotics (includes landers, penetrators, sample return)	• Sampling acquisition • Sample handling and preservation • Earth return	• Core sample collection (on impact)/preserve stratigraphy; automatic sample ejection for orbital capture; multiuse drill, 1 m (goal 10 m) into dirty ice; landing anchoring system (goal: release and reanchor); collection by landers/standoff vehicles/impactors of ice **(1){3}** • In-flight sample transfer; multiuse core storage; hundreds of grams per sample; preserve stratigraphy; preserve volatiles at ~ 150 K **(1){3}** • Earth return capsule for 16 km/sec entry: preserve sample at 150 K **(1){3}**
3.1 On-board autonomy	• Autonomous control and navigation near low-gravity bodies	• Small body modeling (dynamics, etc); Autonomous descent, landing (100 m landing accuracy)/hopping/hazard avoidance, return rendezvous/docking **(1){3}**
2.1 Sensors/ detectors	• Seismometry	• Microseismometer **(3){3}**

Table A2. Small Body Coring and Advanced Sampling Technology Requirements (In addition to requirements in Table 1A)

Technology Element	Technology Area/Item	Performance Metric (Criticality) {Current TRL}
1.6 Robotics (includes landers, penetrators, sample return)	• Sampling acquisition	• Drill or burrow 1 m into regolith, 100 m into dirty ice; collection by landers/standoff vehicles/impactors of ice, regolith, rock metallics **(1){3}**
2.1 Sensors/ detectors	• Insitu composition	• Multiple detectors integrated into miniature organic chem lab **(2){3}**

Table A3. Jupiter Deep Multiprobes Technology Requirements

Technology Element	Technology Area/Item	Performance Metric (Criticality) {Current TRL}
1.1 Power	• Advanced solar arrays (carrier) • Advanced secondary battery (carrier)	• Si: 24% efficiency at 1 AU, -120°C at Jupiter **(2){4}** • Li-ion: 80 Whr/kg+140 Whr/L+15 Ahr**{5}**; or Li-Polymer: 150 Whr/kg+250 Whr/L+ 15 Ahr**{3}(2)**
1.2 Propulsion	• Chem-based (carrier) • Advanced SEP and thrusters (carrier)	• I_{sp}/350s/**(2){4}** • Midterm: 5 kW, < 30 kg/kW (including power system); long term: 10 kW, < 30 kg/kW [including power system] **(2){4}**
1.3 Spacecraft avionics	• High density integrated avionics (carrier and probes) • Attitude control (carrier)	• Microspacecraft architecture/high-density electronics: serial digital interface [MCM]; analog interface [MCM]; SGM DRAM SSR; SGM computer, 100 Mps; RFS uplink [MCM] **(1){2}** • μGyros/drift <0.1 deg/hr; mini prop. drive electronics [MCM]; interface electronics [MCM] **(2){2}**
1.4 Structures/ materials	• Probe entry heat shields (probes) • Multifunctional structure (carrier and probes) • Minimum mass composite pressure shell (probes)	• Ratio of shield mass to total Jupiter probe mass: ~ 35% **(1){3}** • 15—30% mass reduction via embedded electronics structure and cabling **(2){3}** • 25% mass reduction, pressure-safe at 100 bars **(2){4}**
1.8 Thermal control	• Thermal insulation (probes)	• Probe phase change system: to 100 bars [ambient 670 K] **(1){3}**
2.1 Sensors/ detectors	• Lightweight mass spectrometer (probes)	• Total system:#2—5 kg, < 10 W, volume < 5 L **(1){3}**
5.2 Space communications	• Deep space μtransponder • Data acquisition from constellations • Lightweight antenna (carrier)	• Microspacecraft comm. architecture **(2)** • Probes-carrier link: 100 bars **(2){3}** • μspacecraft antenna: supporting architecture and technologies **(2){5}**

Table A4. Solar-Mercury Mission Technology Requirements

Technology Element	Technology Area/Item	Performance Metric (Criticality) {Current TRL}
1.1 Power	• Advanced solar arrays • Advanced secondary battery	• Hi-temp tolerant - 5—10 kg/kW (SEP support); hi-temp with GaAs cells and high-band-gap cells **(1){2}** • Li-ion: 80 Whr/kg+140 Whr/L+25—30 Ahr and useable at 40—50°C; NaS, useable at 200 ± 10°C **(2){3}**
1.2 Propulsion	• Advanced SEP and thrusters or • Solar sail	• Midterm: 5 kW, < 30 kg/kW (including power system); long term: 10 kW, < 30 kg/kW [including power system] **(1){4}** • Areal density: < ~ 6 g/m^2; configuration control, techniques, and mech; modeling and simulation; verification techniques **(1){2}**
1.3 Spacecraft avionics	• Rad-hard microelectronics • High temperature microelectronics	• Rad-hard nonvolatile memory; hi-volume, rad-hard mass storage **(2){2}** • Useable to 200°C "vacuum tube on-a-chip" **(2){1}**
1.4 Structures/ materials	• Advanced composite structures	• Composite tanks, 0.9 system mass fraction **(3){5}**
1.8 Thermal control	• Advanced thermal control	• Thermal blockers; hi-temp MLI; phase change material **(1){4}**

Table A5. Europa Lander Technology Requirements

Technology Element	Technology Area/Item	Performance Metric (Criticality) {Current TRL}
1.1 Power	• Advanced radioisotope power source • Advanced solar arrays	• Efficiency 3X RTG **(1){4}** • 5—10 kg/kW (SEP support) **(1){4}**
1.2 Propulsion	• Advanced biprop systems and components • Advanced SEP and thrusters or • Solar sail	• Near-term: I_{sp}>325 s, midterm: I>350 s, 50% component mass reduction **(1){3}** • 10—20 kW, I_{sp} > 1600 s, increase lifetime of thruster by 2X, increase power throughput of PPU by 93% at 4kW, improve flow control and reduce mass of Xe feed system **(1){4}** • Areal density: < ~ 5 g/m^2; configuration control, techniques, and mechanical; modeling and simulation; verification techniques **(1){2}**
1.3 Spacecraft avionics	• Data handling/advanced CDS	• Rad-hard to 3Mrad: DRAM cubes (SEU immune); µ-packging (MCM interconnects); rad-hard nonvolatile memory **(2){2}**
1.4 Structures/ materials	• Advanced composite structures	• Low mass propulsion tanks **(2){5}**
1.6 Robotics	• Autonomous feature tracking/precision landing	• Precision landing to <2m accuracy**(1){2}**
2.1 Sensors/ detectors	• Insitu composition • Geophysics measurements	• Multiple detectors integrated into miniature organic chem lab (w/µ-GCMS) **(1) {3}** • Miniature geophysics lab, microseismometer **(2){3}**
3.1 On-board autonomy	• Autonomous descent and landing • Landing system	• Architecture, system, and sensor development; real-time image recognition/interpretation **(1){3}** • Landing anchoring system **(2){2}**
4.1 Planetary telerobotics	• Surface mobility • Planetary subsurface systems	• Advanced rover: move tens of km **(3){2}** • Cryobot ice penetrator (second generation lander): penetrate from Europa surface to 100—10,000 m; hydrobot explorer **(1){2}**

Table A6. Io Volcanic Observer Technology Requirements

Technology Element	Technology Area/Item	Performance Metric (Criticality) {Current TRL}
1.1 Power	• Advanced radioisotopic power source • Advanced solar arrays	• Efficiency 3X RTG **(1){4}** • 5—10 kg/kW [SEP support] **(2){4}**
1.2 Propulsion	• Advanced biprop systems and Components • Advanced SEP and thrusters or • Solar sail	• Nearterm: I_{sp} >325 s/midterm: I_{sp}>350 s/ 50% component mass reduction **(1){3}** • Advanced 14cm NSTAR derivative: I_{sp} 3500 s at 1.25 kW PPU output, 2—2.5 kg thruster mass, 50 kg thruster propellant mass throughput, reductions in feed system mass **(2) {4}** • Areal density: < ~ 5 g/m^2 **(2){2}**
1.3 Spacecraft avionics	• Data handling/advanced CDS • Rad-hard spacecraft sensors • Attitude control	•Rad-hard to 100 Mev-cmE2/mg: Power PC603v processor, >33 MIPS; 450 kbps uplink/downlink interface; analog input interface (32 channels); discrete serial I/O (32 channels); 4 M gate array; 4 GB flash nonvolatile memory; 3 Mbps low power serial bus; μ-packaging (MCM interconnects) **(1){2}** • Active pixel sensor rad-hard version of x2000 Star camera; coarse sun sensor; advanced rad-hard MCM star tracker and sun sensor interface **(1){2}** • Advanced rad-hard hemispherically resonating gyroscopes; advanced rad-hard micromachined accelerometers; advanced MCM IMU support electronics; magnetic bearing reaction wheels and drive electronics; advanced rad-hard MCM propulsion drive/drive units; advanced remote agent autonomy including on-board autogenera-tion/execution of maneuver sequences, target identification, and autotracking; autonomous image motion compensation; autonomous predictive pointing for optical com **(1){2}**
1.4 Structures/ materials	• Multifunctional structures	• 15—30% mass reduction via embedded electronics structure and cabling **(2){3}**
2.1 Sensors/ detectors	• Advanced PICS/LIDAR/IR	• Integrated remote imaging instrument [12.5 kg/11 W] **(1){3}**
3.1 On-board autonomy	• Autonomous processing	• Autonomous data compression, autonomous software controlled BITE; on-board pattern recognition system; on-board dynamic sequencer; autonomous on-board image analysis/target pattern recognition/science classification/priority determination for downlinking **(2){2}**
5.2 Space communications	• Optical communications	• Downlink optical communications required for high data rate; receiving stations at < $3000/pass **(2){4}**

Table A7. Neptune Orbiter/Triton Exploration Technology Requirements

Technology Element	Technology Area/Item	Performance Metric (Criticality) {Current TRL}
1.1 Power	• Advanced radioisotopic power source • Advanced solar array • Advanced secondary battery	• Efficiency 3X RTG **(1){4}** • CIS solar array technology, 10—12% efficiency by '04; concentrators; inflatables; hi-voltage solar array (for SEP) **(1){4}** • > 11 year lifetime **(2){3}**
1.2 Propulsion	• Advanced SEP and thrusters	• Midterm: 5 kW, < 30 kg/kW (including power system); long term: 12—24 kW, < 30 kg/kW (including power system) **(1){4}**
1.3 Spacecraft avionics	• Data handling/advanced CDS	• Power PC603v processor, >33 MIPS; 450 kbps uplink/downlink interface; analog input interface [32 channels]; discrete serial I/O [32 channels]; 4 M gate array; 4 GB flash nonvolatile memory 40 Mbps fire wire serial bus; μ-packaging [MCM interconnects]; low-temperature electronics **(2){2}**
1.4 Structures/ materials	• Aerocapture system	• Aerocapture system mass to total system mass ratio of 25—35% **(1){2}**
2.1 Sensors/ detectors	• Advanced remote sensing instruments	• PICS [3 kg/3.5 W]; ISPI [2 kg/2.8 W]; thermal mapper [2.5 kg/6 W] **(1){3}**
3.1 On-board autonomy	• Autonomous processing	• Autonomous data compression, autonomous software controlled BITE; on-board pattern recognition system; on-board dynamic sequencer; autonomous on-board image analysis/target pattern recognition/science classification/priority determination for downlinking **(1){2}**
5.2 Space communications	• Optical communications	• Downlink optical communications required for high data rate; receiving stations at < $3000/pass **(2){4}**

Table A8. Titan Organic Explorer Technology Requirements

Technology Element	Technology Area/Item	Performance Metric (Criticality) {Current TRL}
1.1 Power	• Advanced radioisotopic power source • Advanced solar array	• Power stick (RHU-based power source) or small AMTEC system **(1){3}** • 5—10 kg/kW (for SEP support) **(1){4}**
1.2 Propulsion	• Advanced SEP and thrusters	• Midterm: 5 kW, < 30 kg/kW (including power system); long term: 10 kW, < 30 kg/kW (including power system) **(1){4}**
1.4 Structures/ materials	• Aerocapture system	• Aerocapture system: <35% of entry mass **(1){3}**
2.1 Sensors/ detectors	• Insitu composition • Insitu atmospheric dynamics • Geophysics measurements	• Multiple detectors integrated into miniature organic chem lab **(1){3}** • Microinstruments: pressure, density, temperature, wind speed **(2){4}** • Miniature geophysics lab, microseismometer **(2){3}**
3.1 On-board autonomy	• Autonomous aerobot operations	• Mobility using winds; excursions to surface; sample collection with snake; on-board navigational sensing and perception; autonomous navigation; tropospheric altitude control systems to withstand Titan atmosphere and 500g entry **(1){2}**
4.1 Planetary telerobotics	• Aerobot advanced buoyancy concepts • Aerobot surface proximity guidance and control	• Advanced concepts for Titan atmosphere **(2){2}** • For aerobots at Titan: 500g entry, 5 mbar to 2 bar pressure **(2){2}**

Table A9. Venus Laboratories Technology Requirements

Technology Element	Technology Area/Item	Performance Metric (Criticality) {Current TRL}
1.1 Power	• Advanced solar array	• Gondola system; survivable with thermally robust to 460°C/92-bar and high-g entry **(1){?}**
1.3 Spacecraft avionics	• Advanced CDS	• High density integrated avionics; MCMs for various functions; integrated structures/low-mass cabling and connectors **(1){3}**
1.4 Structures/ materials	• Remote sensing support • Entry system	• Imaging window **(1){?}** • Parachute design **(1){~6}**
1.8 Thermal control	• Advanced thermal control	• Active cooling/high temperature electronics; phase change thermodynamics (Venus atmosphere and surface) **(1){?}**
2.1 Sensors/ detectors	• Insitu atmospheric dynamics • Geophysics measurements	• Microinstruments: pressure, density, temperature, wind speed **(2){4}** • Miniature geophysics lab, microseismometer **(2){3}**
3.1 On-board autonomy	• Autonomous aerobot operations	• Mobility using winds; excursions to surface; sample collection with snake; on-board navigational sensing and perception; autonomous navigation; tropospheric altitude control systems to withstand Titan atmosphere and 500g entry **(1){2}**
4.1 Planetary telerobotics	• Aerobot advanced buoyancy concepts • Aerobot surface proximity guidance and control	• Balloon envelope: advanced concepts for Venus atmospheres, 75—730 K temperatures, sulphuric acid clouds/COO atmos's; deployability **(1){2}** • For Aerobots at Venus: 500-g entry, 5 mbar to 95 bar pressure, 75—730 K temperatures, sulphuric acid clouds/CO_2 atmospheric **(1){2}**
5.2 Space communications	• Deep space communications	• Direct-to-earth communications (including closed loop steerable antenna) **(2){5}**